

HYBRIDIZED THERMOPLASTIC ARAMIDS: ENABLING MATERIAL TECHNOLOGY FOR FUTURE FORCE HEADGEAR

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ABSTRACT

U.S. Army ballistic helmet manufacturing has not changed significantly in nearly 30 years. Advances in U.S. helmet technology have been largely in shell design, improved aramid fibers, and helmet liner and suspension systems. The Army is currently replacing its first composite ballistic helmet, Personnel Armor System Ground Troops (PASGT), with the Advanced Combat Helmet (ACH). ACH has undergone ballistic testing and system analysis with improvements to weapons and body armor interfacing issues. Still, ACH uses some of the same materials (butyl rubber toughened phenolic resin with aramid fabric reinforcements) and the same process technology as its 30 year old PASGT predecessor. The current research effort has focused on identifying and resolving technology barriers that limit a new and improved generation of ballistic materials from being considered for use in future helmet systems. Both historical and contemporary perspectives of ballistic helmet technology are provided as rationale for the development of alternative helmet materials and their associated processes. The primary technology barriers are four-fold: structural durability (static and dynamic deformation), contiguous preform construction (less cutting of the reinforcement without wrinkling), hybridization of dissimilar fibers and resins, and low cost manufacturing (rapid heating, consolidation, and cooling of tools and parts). Flat plates and full helmet shells were molded to quantify the performance and benefits of hybridized materials to meet current and future demands for increased ballistic mass efficiency.

1. INTRODUCTION

The introduction of the PASGT helmet (McManus et al., 1976) in the late 1970s *revolutionized* head-borne ballistic protection for the individual soldier. From World War I until the conclusion of the Vietnam war, Hadfield steel was the outer shell ballistic material in the standard issue US military helmets. The commercialization of the para-aramid polymer, Kevlar, enabled a helmet that had an average of 30% more ballistic protection at the same total weight of the two-part steel-based helmet it replaced. Only recently has the Army begun replacing the PASGT helmet with the Advanced Combat Helmet (ACH), which

uses improved strength (Riewald et al., 1991; Yang, 1993) aramid fibers (Kevlar K129, KM2 and Twaron are all higher performance para aramids), but still uses thermoset phenolic matrix materials and molding processes that are more than 60 years old.

There are new helmet efforts on the horizon, as well as opportunities to introduce materials and process improvements to the current ACH helmet. The Future Force Warrior (FFW) Program, for example, demands a helmet that is lighter than the current ACH helmet system. FFW is the precursor to the Ground Soldier System (GSS). FFW weight reduction requirements are driven largely by the desire to accommodate head-borne electronic devices without exceeding a total headgear weight of about 5.5 lbs. The challenge is delivering increased capability and supporting the weight of the new hardware without sacrificing the ballistic protection and integrity of the helmet shell. Figure 1 illustrates some of the past, current, and future U.S. helmet technologies.

There are several challenges in developing a new set of materials for use in future U.S. Army systems. The primary technical barrier is to deliver a safe, durable, robust helmet system at lighter weight. Another concern is the ability to introduce these materials effectively by offering a process to the current manufacturing infrastructure to optimally manufacture the helmet shells *en masse*. Finally, there are economic and affordability issues that will influence domestic U.S. helmet manufacturers. Replacing traditional – and largely effective – helmet manufacturing equipment is a serious capitalization and investment decision.

2. BACKGROUND

The PASGT helmet has been in service for nearly 30 years. Its design has been adopted or imitated by military, police and other agencies both in the United States and abroad. The fact that it has enjoyed such long and successful utility poses interesting questions for future helmet programs. Evolving U.S. helmet technology will likely benefit from smaller, more frequent changes in helmet design and materials. Helmet variants produced by these endeavors allows for technology assessment –

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 01 NOV 2006		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Hybridized Thermoplastic Aramids: Enabling Material Technology For Future Force Headgear				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory Weapons & Materials Research Directorate Aberdeen Proving Ground, Maryland, 21005-5069				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM002075., The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 30	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			






	WWI	WWII/Korea/Vietnam	PASGT	MICH/ACH	FFW
Design					
Material	Rolled steel	Hadfield Steel	Kevlar 29/PVB Phenolic	Kevlar 129/PVB phenolic Twaron/PVB phenolic	Thermoplastic aramid Spectra/Dyneema Hybrids
Areal Density (psf)	2.3-2.4	2.3-2.4	2.3-2.4	2.0-2.1	1.5-1.8
Threat	Shrapnel	Fragmentation	Fragmentation 9mm bullet	Fragmentation 9mm bullet	Fragmentation 9mm bullet

Fig. 1. Past, current, and future U.S. Army helmet systems

and migration. An excellent example of technology migration is the development and production of the ACH. The ACH is a helmet currently being fielded to the general Army but it had its origins in MICH (Modular Integrated Communications Helmet). The MICH was developed for the Special Forces engaged in missions where hearing is crucial, as is the ability to communicate information stealthily and efficiently.

It is instructive to consider the forces that ultimately led to the ACH helmet, primarily because it provides a potential path for introducing a new generation of materials and processes, as well as modifications to the design and configuration of the helmet system. Furthermore, changes in the Army's procurement specifications have allowed domestic manufacturers more freedom to develop innovative approaches that had been more difficult to pursue under traditional military specification ("MIL Spec") doctrines.

2.1 Military vs. Performance Specifications

The traditional approach in helmet development was for the U.S. government to explicitly define not only performance parameters for a helmet, but the types of materials and processes that may be considered. In essence, the MIL Standards provided a step-by-step approach on how to fabricate the helmets; it was up to the helmet manufacturers to reduce to practice and scale up for production. In the early 1990's, the U.S. Army transitioned to performance-based specifications. This transition has a number of critical differences from MIL specs, but primarily performance specification defined quantitative and objective criteria and requirements. It does *not* specify the types of materials or processes that may be considered. As such, performance specifications have enabled domestic helmet manufacturers to consider materials from several perspectives, including foreign sourced materials such as Twaron (an aramid similar to Kevlar but produced in the Netherlands).

It is important to consider the impact of performance specs as they directly influence – if not enable – the introduction of more mass efficient ballistic material and improved manufacturing processes. The MICH helmet used an improved toughness Kevlar, increased the reinforcement content, changed to foam pad suspension and a new geometric design that removed nearly 10% of the surface coverage of the helmet. The latter was done to improve helmet interfacing with both weapons and body armor, as well as improved hearing, communication, and situational awareness capability. The total weight of the helmet was reduced. The subsequent success of the MICH ballistic shell and suspension system led to the development of the Advanced Combat Helmet. The ACH and Future Force Warrior both provide opportunities to introduce improvements in helmet materials and systems. Introduction of these improvements are largely enabled by performance based specifications.

2.2 Historic Perspective of Helmet Materials

It has been demonstrated with historical evidence as early as 1915 (Dean, 1920) that considerable thought had been given to the design of a "modern" combat helmet shell. The German designs were particularly advanced and demonstrated a more sophisticated assessment of threats. Advances in metallurgy provided a path for introducing both improved performance and near-net shaping of helmet shells from steel. This includes the development of Hadfield steel and its ultimate deep-draw cold forming into the U.S. Army's M1 "steel pot" helmet shell. The M1 helmet remained in service through the end of the Vietnam war. The PASGT helmet ultimately replaced the M1 and was a change in both design and material. The laminate material of the PASGT has a ballistic efficiency greater than 30% higher than that of the M1 steel. Even with the improved nylon reinforced phenolic liner used in some of the later M1 helmet systems, the Kevlar material alone allowed for both higher protection levels and greater surface area of coverage. This was achieved while keeping the complete helmet weight the same.

The SOF requirements defined the design and material selection of the MICH helmet. For example, a lighter helmet was required and hence an improved aramid fiber (Kevlar 129) replaced the traditional Kevlar 29 that had been used in previous helmets. The MICH uses a higher cut line around the bottom edge to improve interfacing with body armor and the ability to mount and aim weapon systems. Modifications around the ear of the helmet enabled improved hearing capability, critical to SOF personnel in stealthy environments. Many of these improvements were adopted in the Advanced Combat Helmet.

More recently the trend has been to develop helmet designs, materials, and systems that reduce weight. Total helmet weight and ballistic protection are the critical parameters in overall helmet design. Adverse air-drop load on the neck is a primary weight-limiting factor. Typically, the maximum head-borne load that can be supported by air drop is 5.5 lbs. This weight must include all elements of the helmet – shell, suspension, communication equipment, sensors, fabric covers, and all sub-systems and attachments. The development of more mass-efficient ballistic materials enables the consideration of two distinct helmet design approaches. The first and most obvious is the ability to deliver the same level of performance of current helmets at lighter weight. The second possibility is to deliver a helmet that is essentially the same weight of current systems but demonstrates a higher level of ballistic protection. It is also possible to increase the area of ballistic coverage without exceeding the weight of the original baseline helmet.

2.3 Potential of Thermoplastic Materials

There are two generic classes of materials that have already demonstrated the potential for significant weight savings. The first involves a high performance laminate of cross plied unidirectional layers of high strength fibers with a compliant resin matrix. Commercial products Spectrashield or Dyneema use ultra high molecular weight polyethylene (UHMWPE) fibers with thermoplastic elastomer matrices. The properties and use of these materials have been well described elsewhere (Scott, 2006; Cunniff, 1999). The second class of ballistic laminate materials involves woven fiber reinforcements, similar to existing PASGT and ACH systems, but with much more compliant thermoplastic matrices (Walsh et al., 2005). While this thermoplastic bonded aramid fabric combination has been recently used in helmets abroad (Effing et al., 1994), it has not seen significant activity in U.S. helmet development. We are exploring, predominantly, the latter aramid fabric class because it allows the unique ability to compare transitional helmet materials (i.e. thermoset phenolic) with variants being explored under this research but using similar manufacturing tooling and processes. Aramids can be

combined with either thermoset and thermoplastic resin systems, with associated modified processing conditions. As such, aramid fibers such as Kevlar and Twaron allow for a direct comparison of the influence of the matrix materials on key parameters such as ballistic mass efficiency, structural and dynamic deformation, and processing conditions.

Thermoplastic matrices (Figure 2) have relatively low brittleness transition temperatures which allow potential improvements in three critical attributes: greater ballistic resistance, higher mechanical toughness, and faster manufacturing cycles. By contrast, the rubber toughened phenolic resins (of the type used in PASGT and current ACH helmets) are thermosets resulting in a cross-linked chemical structure upon complete cure of the resin. This chemical reaction is the rate limiting step in the manufacture of helmets, often requiring 15-30 minutes of in-tool process time at temperatures of approximately 300 degrees F. Thermoplastics do not require such a cure reaction; instead the material melts, flows, and solidifies around the aramid fabric and is controlled by the rate at which thermal energy is added and removed.

2.4 Mechanics of Compliant Matrix Composite Armor

The mechanisms of fragment arrest with this more compliant matrix material class have been previously identified (Scott, 1999). Figure 3 presents a crosssection of a relatively thick aramid reinforced, polyolefin matrix laminate, partially perforated by a rifle bullet at typical ordnance velocity.



Fig 2. Thermoplastic coated aramid

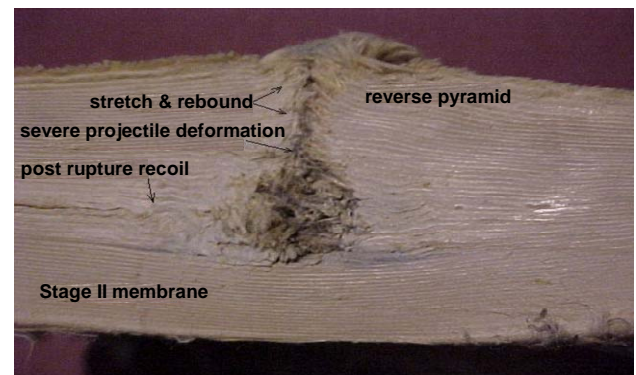


Fig. 3. Post penetration arrest fiber damage

It is apparent that the nature of the failure of the reinforcement changes from the impact side to where the projectile is finally arrested. Figure 4 presents a sketch of what is hypothesized to have occurred during the event.

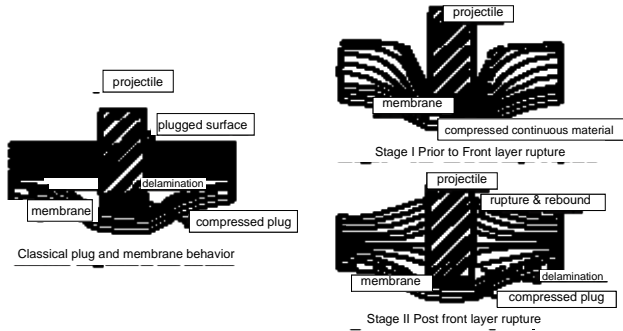


Fig. 4. Simplified description of the penetration process of a rigid cylinder into a ballistic laminate.

Others (Bless et al., 1999; Woodward et al., 1994) have attempted to identify the predominating failure modes in similar configurations. In general, perforation occurs after transverse shear and transverse compression failure of the frontal plies. Once the projectile decelerates and energy is transferred to the remaining plies, a membrane like deformation then accommodates the residual momentum of the slowed projectile. Of course if the impact conditions are severe, the remaining capacity of the backface membrane will be exceeded and the projectile will perforate. The important armor design implication is that optimization of a single mechanism is not going to result in an optimum final product. Indeed, previous studies have suggested optimums for the impact face correlate with transverse shear strength and the backface optimum may be more associated with the extent of deflection (capacity of membrane energy).

We have recently performed simple short beam shear tests on a wide range of these candidate armor materials as a means of estimating transverse shear strength from estimates of the interlaminar shear strength. No correlation of ballistic efficiency verses transverse shear strength is apparent in Table 1 since the membrane response of monolithic panels would overshadow the benefit of higher shear resistance on the impact surface. It does identify a trend however that higher pressing pressures generally yield higher shear strengths in both of the resin matrix classes. The purpose of the present study is to examine the viability of a hybrid thermoplastic solution while certainly considering the process implications (e.g., dissimilar materials, multiple process steps, bonding and assembly methods).

Table 1. Short Beam Shear estimates of interlaminar shear strength or transverse shear strength

Material	Shear Strength (psi)	Shear Strength (Mpa)	Avg. P _y (lbs.)
KM2_Phenolic (HP)	434.99	3	47.47
KM2_Phenolic (LP)	284.99	1.96	32.97
KM2_Phenolic (HP)_Shot	706.16	4.87	87.55
KM2_Phenolic (LP)_Shot	481.12	3.32	61.78
Kevlar_TP (HP)	364.48	2.51	41.76
Kevlar_TP (LP)	60.97	0.42	7.62
Dyneema HB25 (HP)	32.02	0.22	6.27
Dyneema HB25 (LP)	24.37	0.17	4.95
Dyneema HB2 (HP)	22.42	0.15	4.1
Dyneema HB2 (LP)	19.37	0.13	3.64

The logical approach to identifying optimum armor designs is to consider hybridization. Recognizing that the impact side of the laminate will see the projectile at its greatest velocity where there is insufficient time to develop strain in the fiber, we should select a material which exhibits good resistance to shear plugging instead of membrane rupture. On the back side we would want to have a material with ductile rupture strength. The materials listed in Table 1 above all satisfy the latter desire. If one accepts that a more rigid, high shear strength layer should be used on the impact side for ballistic purposes, its advantageous to make this same layer perform a structural role. This is the governing approach that we will pursue to minimize weight and resist perforation while at the same time, provide sufficient structural rigidity to limit deflection during ballistic impact or during normal handling conditions. Once the desired material combination is identified, the greater challenge of how to manufacture it will follow.

3. EXPERIMENTAL PROCEDURES

US ballistic helmets typically have a wide range of requirements. They can include everything from limit velocity (V50) tests with fragment simulators to measurements of kinetic energy extraction. The generally specified fragment weights are 2,4,16,17 (1.1 gram), and 64 grains. Yet another requirement is stopping the 124 grain full metal jacketed 9mm bullet. These tests are conducted under ambient, cold (~ 50 deg below zero) and hot (~150 deg F) conditions. To explore and characterize the performance of thermoplastic materials, a strategy was developed to screen potential candidate materials (and material combinations) prior to helmet shell fabrication. Flat plate specimens measuring 15"x15" were fabricated from multi-layered combinations of compliant ballistic materials with fewer layers of structural skin material and their ballistic resistance was measured. The core material used was a polyolefin coated aramid (600 denier Kevlar KM2) fabric. The candidate materials are shown in Table

II. 2 grain and 17 grain are typically selected as primary screening projectiles. The panels were installed in a ballistic range so that the backface deformation could be measured in a non-contact manner (Figure 5). It can be argued that the use of clay-based backing materials interferes with the maximal back face deformation. A digital high speed Phantom VII camera captures and measures the unrestrained maximal deformation.

Table II. Material components

Matrix	Fiber	Architecture
Polyethylene	Aramid	woven fabric
Nylon	Carbon	cross ply uni
TP elastomer	Glass	stitch bond
Epoxy	UHMWPE	

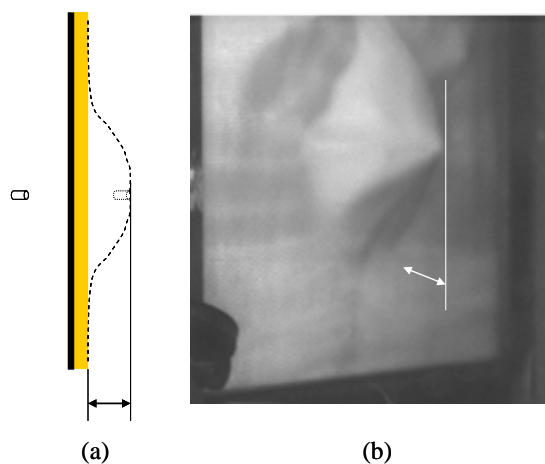


Fig. 5. Dynamic deflection measurement

In addition to ballistic and dynamic deflection measurements, constituent thermoplastic aramids were examined using scanning electron microscopy (SEM). For the woven family of materials, we prefer to have the resin not wet-out the filaments within a yarn, but instead bond the individual plies together. Finally, mechanical data was generated using both 3-point beam flexural and short beam shear tests. Flat panel data is useful as a preliminary screening procedure but composite materials perform differently when molded into a geometrically complex shape. As such, to properly characterize real material performance it is necessary to test the materials in the shape of the actual helmet shell. A helmet shell fabrication capability was developed which included: an 800 ton press, helmet tooling, preforming, and consolidation controls. Figure 6 demonstrates the fabrication of a partially stabilized helmet “preform”

which can either be tested as a lower pressure variant or subjected to further consolidation using matched metal tooling, hydroclaves, and other processes. Several helmet variants were produced based on prior flat plate candidate material results.



Fig. 6. Silicon plug, metal female cavity, thermoplastic preform placement

The majority of these candidates included structural skins on the outer surface where ballistic and structural demands dictated. Figure 7 provides an example of the range in material combinations and helmet geometry (PASGT, ACH, FFW).



Fig. 7. Representative sample of helmet shell variants

These candidate helmet shells were subsequently subjected to ballistic testing, including 2 and 17 grain V50 measurements and the recording of the peak backface deformation using the high speed digital visualization. The helmets were also subjected to a “crush test” in order to estimate their field durability. This test involves the cyclic application of a 300 pound force across the ear side walls for 25 cycles without a permanent deformation exceeding the order of 1/8 inch. A crush test fixture was built and installed on an Instron load frame (Figure 8). The residual deformation in the helmet immediately after, and 1 day after the loading is measured. Generally this is

reported as a pass/fail based on the threshold criteria defined in performance specifications.



Fig. 8. Crush test

4. RESULTS AND DISCUSSION

Examination of the as-laminated thermoplastic-coated aramid fabric yielded interesting surface features associated with the adherence of polyolefin resin to the woven fibers. It is apparent in lower Figure 9 that high and low contact points are present as the fiber bundles undulate in the fabric pattern. These high and low points provide areas of good adhesion and poor adhesion. Upper Figure 9 shows the thermoplastic coating appearance once it has been fully consolidated on a surface. It is clear that sustained application of heat and higher pressure improves adhesion of the thermoplastic to the overall woven Kevlar fabric.

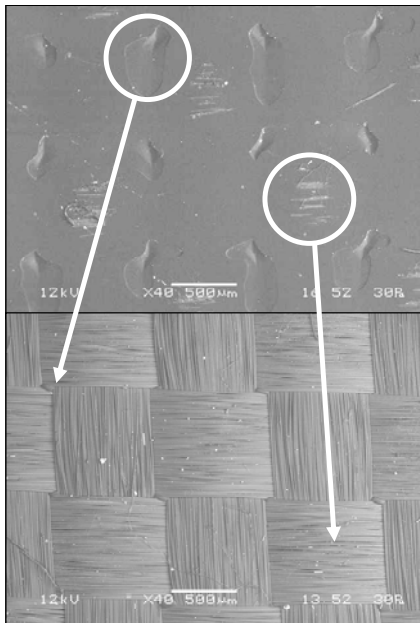


Figure 9. SEM of Thermoplastic aramid

It is critical for a rigid structural skin to be well adhered to the compliant ballistic core material. The ballistic material would never pass the cyclic compression test by itself, even at room temperature. The overall shell rigidity is dependent upon the stiffness and thickness of the applied skin. The stiffer the cured skin, the stiffer the final shell. Adhesion between skin and core is critical. We had selected thermoset epoxies as the matrix of the skin with good structural compatibility between fiber and resin. In addition we had to ensure that the epoxy used was chemically compatible with the thermoplastic resin of the core and that we could cure it at a temperature compatible with the thermoplastic molding cycle. Additional care had to be applied to ensure that delamination between skin and core would not occur even though the two materials likely had residual stresses resulting from the cool down of the two dissimilar coefficients of thermal expansion.

Combinations of skin and core materials were identified which were compatible chemically and thermally and which held together sufficiently to pass durability and ballistic limit requirements. Several process variations were attempted, all with less than ideal manufacturing efficiency. Wrinkling, assembly time, molding time, tooling complexity, and quality issues still remain to be resolved.

4. 1 Examination of Hybrid Solutions

Flat panel testing of monolithic thermoplastic Kevlar provided an opportunity to compare the thermoplastic composite with other material combinations. It is apparent from this study that further performance benefits are possible through material hybridization and novel processing. The properties that make these materials desirable for reduced weight ballistic applications unfortunately complicates their design for structural purposes. Test results of both shells and plates yielded a number of potentially adequate candidates. One of the helmets was sectioned to reveal the damage created during the V50 ballistic testing (Figure 10). The addition of both the thermoplastic and thermoset carbon skins significantly reduced back face deflection. Similar results were observed for the crush test. The most efficient solution in this study was a combination of thermoplastic Kevlar with an IM7 graphite/ epoxy skin. It should be noted that this solution was difficult to fabricate for several reasons which included: cutting and conformance of the IM7 prepreg to the curved helmet surface, leeching of resin into the neighboring thermoplastic plies, and the need to co-process two highly dissimilar composites (a thermoplastic aramid and a thermoset carbon composite). The thermoplastic based skins were notably more compliant than the thermosets, but they have the advantage of being co-processable.

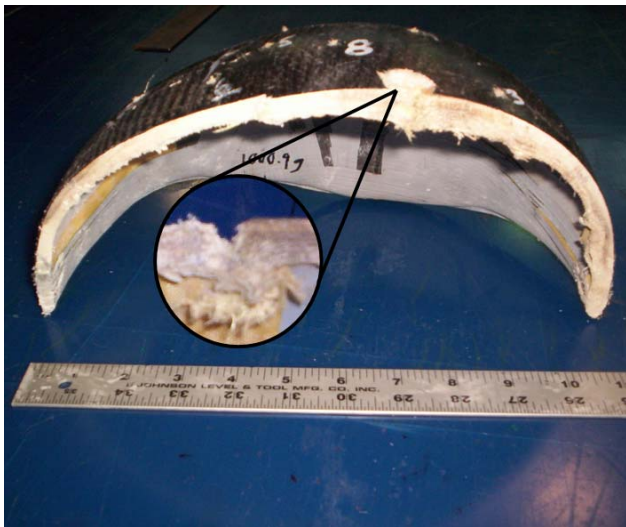


Fig. 10. Sectioned helmet with details of V50 testing

One area of possible innovation is the means by which “secondary” elements are attached to the helmet. For example, the suspension and chin strap system in both PASGT and ACH helmets are affixed using 4 screws. This approach appears to be a legacy of the original M1 steel pot helmet liner. However, from a materials perspective, it is not desirable to introduce holes in the composite shell material for mounting purposes. Unlike the M1’s monolithic, isotropic Hadfield steel, PASGT and ACH use multi-ply woven aramid architecture which introduces many surfaces or discontinuities into the laminate. Both static load and shock transmission through the individual fibers, yarns and layers is far more complex.

As part of this study, a novel helmet was produced that will enable three desirable features: 1) the ability to selectively stiffen the helmet to minimize weight; 2) eliminate the need for drilling holes, and 3) a means for improving the manufacture and assembly of the helmet system using fewer parts. This concept uses a modular carbon composite stiffener, which is manufactured separately, then readily attached to the helmet with adhesive (Figure 11).

4.2 Monolithic vs. Engineered Structure

Nearly all U.S. ballistic helmets have been manufactured in a similar way. The concept of selectively stiffening structures has been thoroughly embraced by the aerospace community. Helmets, by contrast, have been largely monolithic – made from either steel or aramid/phenolic composite. The latter has provided both the ballistic and structural properties required by the helmet specifications. However, as emphasis on producing lighter helmets is increased, a two-fold impact is observed on both the static and dynamic response of a helmet. First, the more ballistically efficient fibers and thermoplastic resin

systems are inherently “softer” than corresponding thermoset systems. Second, less material is used which results in a thinner helmet. This effect is amplified by moment of inertia considerations, which relates flexural stiffness with a cubic function of thickness.

Several thermoplastic-based candidates have been identified for FFW. The lighter, more compliant thermoplastic matrices require additional modification to address the durability and trauma concerns. It is possible



Fig. 11. Integrated helmet stiffener and suspension concept

to preserve the mass-efficient ballistic properties of the polyolefin-based matrix systems by hybridizing the shell with a carbon-based structural composite “skin.” The skin provides shell stiffness, which allows for normal field loading without permanent distortion and limits the deflection during projectile arrest, thereby minimizing the extent of trauma to the skull. A trend has been observed between laminate flexural stiffness and its ballistic efficiency. Figure 12 presents this inverse relationship where the rigidity can be adjusted by selection of variable reinforcement stiffness, resin matrix compliance or fractional resin content.

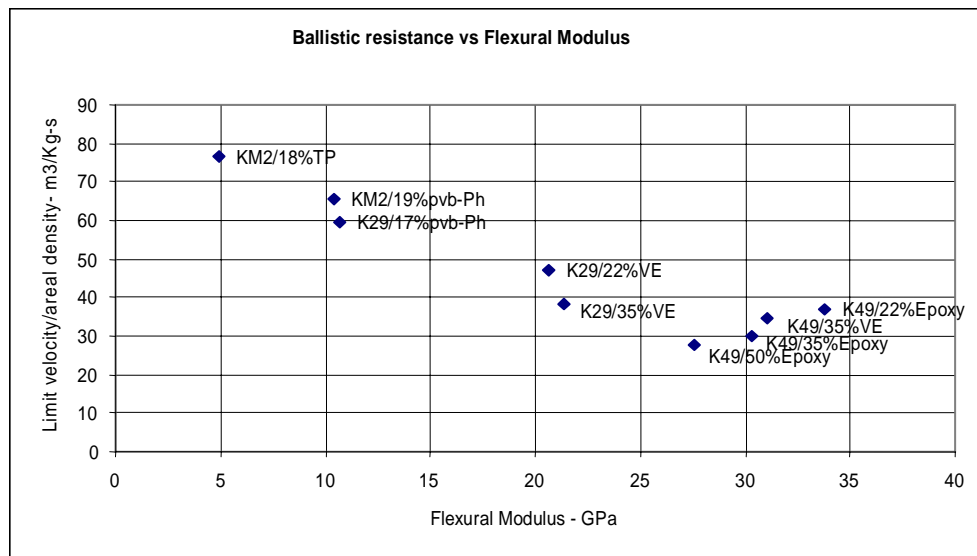


Fig. 12. Correlation of flex modulus with ballistic efficiency

5. CONCLUSIONS

This work has demonstrated that it is possible to construct a lighter, improved helmet from a relatively new generation of thermoplastic matrix-based, fiber reinforced systems. New materials enable reconsideration of heretofore impractical designs. Variants of the thermoplastic-based helmets were fabricated and their performance validated through standard helmet testing protocols. Testing included high speed digital imaging to measure and characterize back-face deformation, 2 and 17 grain fragment simulator V_{50} ballistic evaluation, and ear-to-ear cyclic structural loading. The resulting effort has produced a collection of material candidates with varying levels of ballistic efficiency, structural stiffness, extent of deflection and process complexity from which we can select specific optimums. The primary conclusion is that hybridized thermoplastic matrix aramid materials enable the weight reductions required to meet the current and future demands for improved ballistic efficiency.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions and support given to them by: Scott Grendahl, Paul Moy, Ryan McCuiston, and Matthew Motyka, all of the Army Research Laboratory; Dave Krasnecky and Matthew Correa, both of the Natick Soldier Center; Gary Robblee and Vasilios Brachos, both of Diaphorm LLC; Dave Rogers and Duco Nordicz, both of Artisent.

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Army Science Conference

30 November 2006

Shawn M. Walsh






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U.S. Army Research Laboratory

MOTIVATION & OBJECTIVES

- Current U.S. helmet material technology still uses an aramid/PVB phenolic-based composite
- U.S. helmet manufacturing technology has not changed in nearly 30 years
- In-theater threats increasing
- Weight burden on warfighters has increased
- Future programs demand more ballistically efficient materials to:
 - *Reduce soldier-borne weight or...*
 - *Increase level of protection at current system weight*
- Goal is to identify aramid-based ballistic solutions with improved ballistic mass efficiency

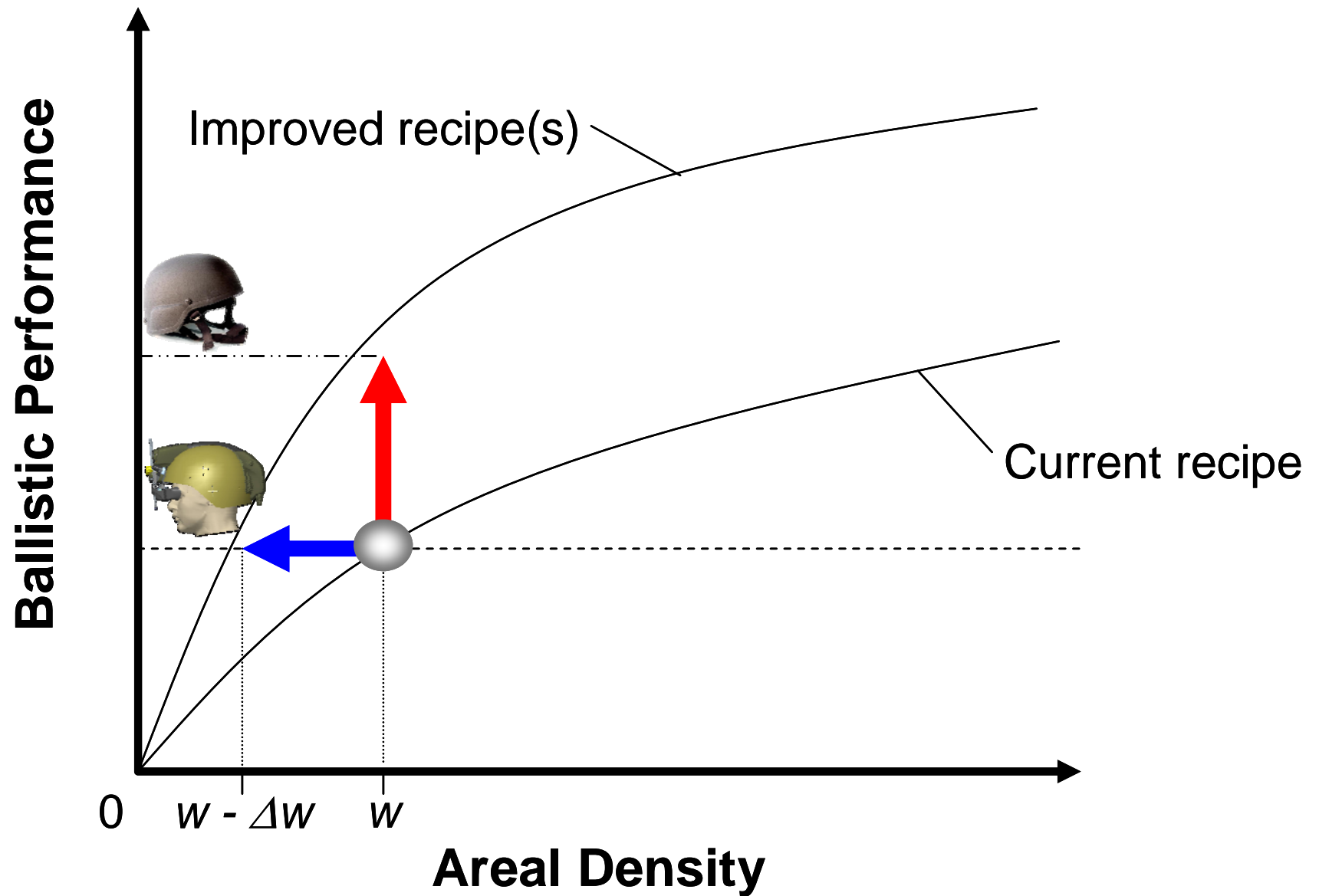
HISTORY OF U.S. ARMY HELMET DEVELOPMENT

	WWI	WWII/Korea/Vietnam	PASGT	MICH/ACH	FFW
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Threat	Shrapnel	Fragmentation	Fragmentation 9mm bullet	Fragmentation 9mm bullet	Fragmentation 9mm bullet

FUTURE FORCE WARRIOR: INTEGRATED SYSTEM



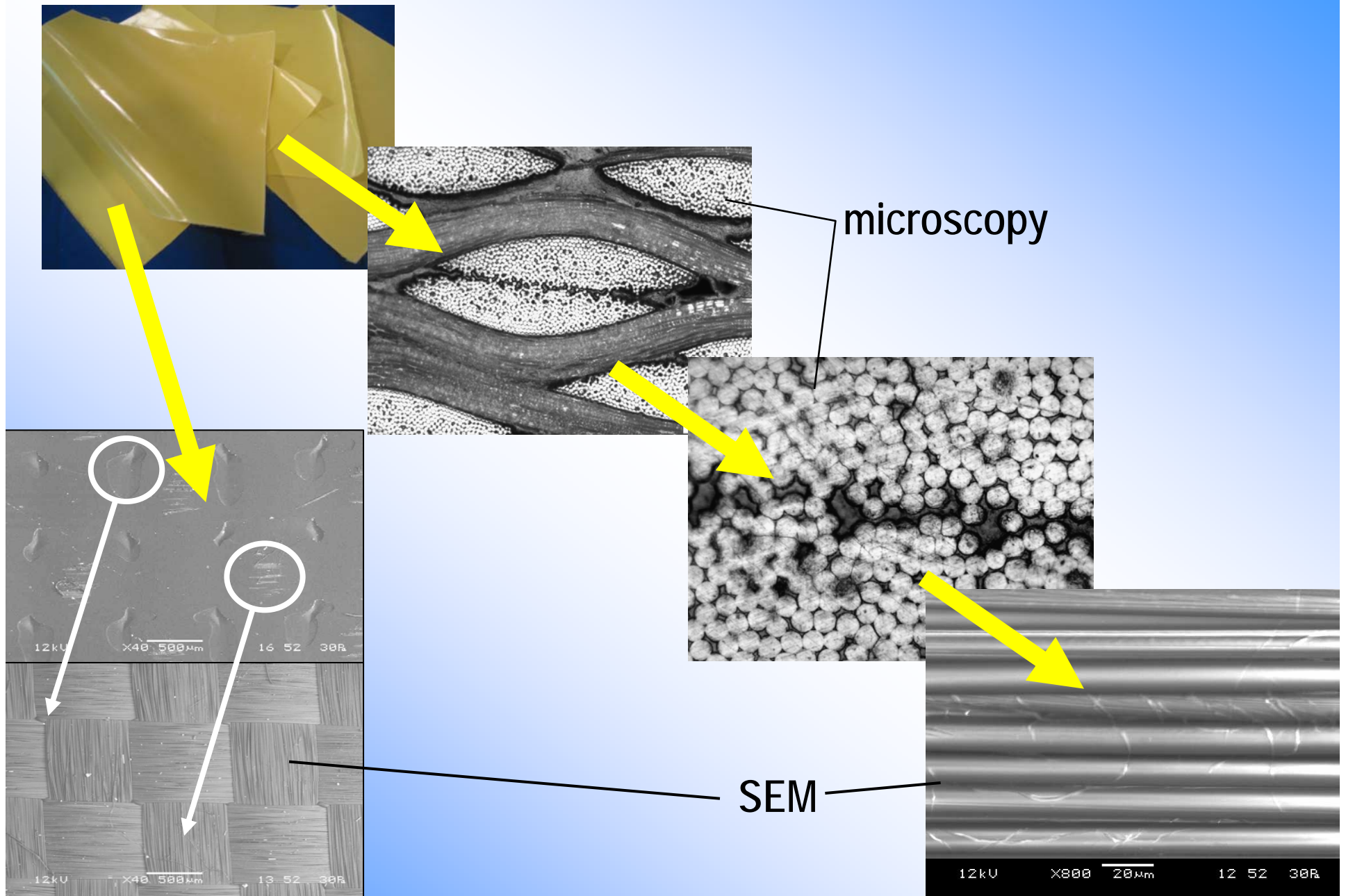
BENEFITS OF IMPROVED BALLISTIC MASS EFFICIENCY



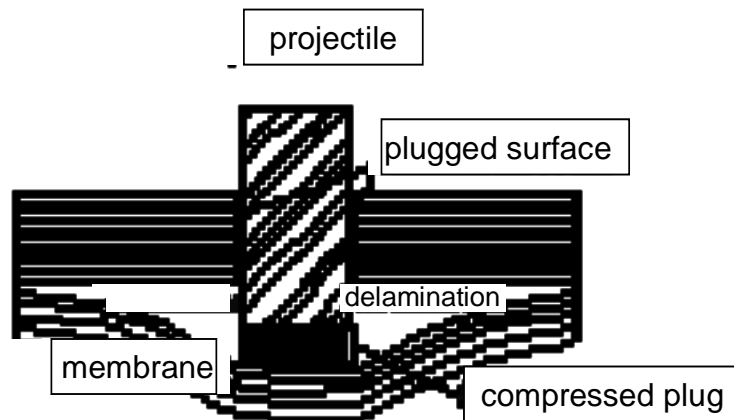
CANDIDATE MATERIALS FOR IMPROVED BALLISTIC EFFICIENCY

Matrix	Fiber	Architecture
Polyethylene	Aramid	woven fabric
Nylon	Carbon	cross ply uni
TP elastomer	Glass	stitch bond
Epoxy	UHMWPE	

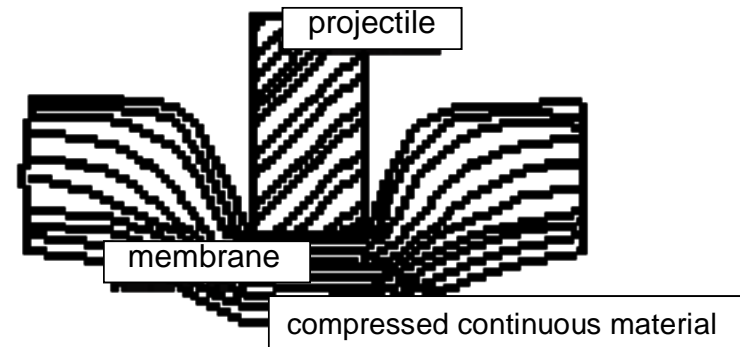
DETAILS OF POLYOLEFIN-BASED ARAMID



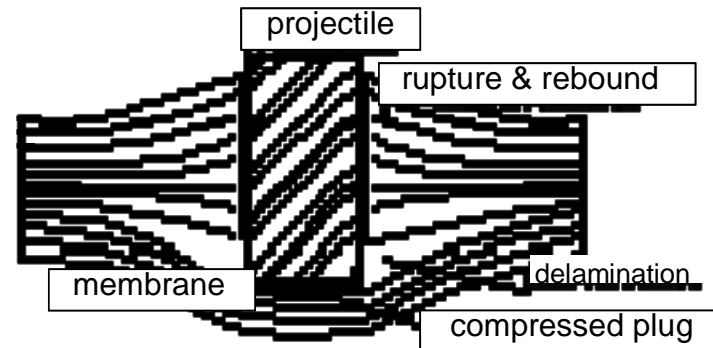
BEHAVIOR OF ARAMID COMPOSITE DURING BALLISTIC EVENT



Classical plug and membrane behavior



Stage I Prior to Front layer rupture

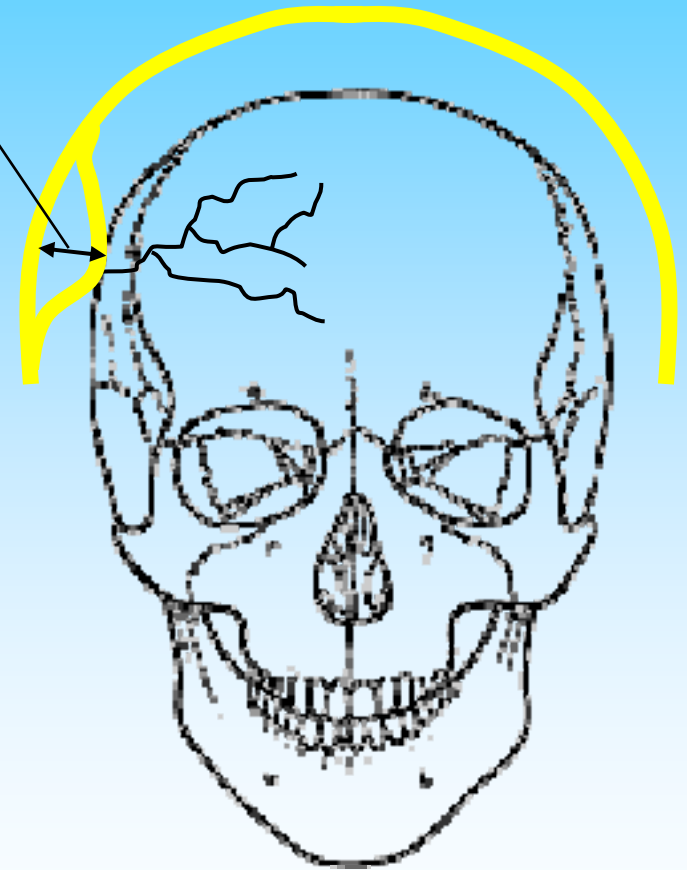
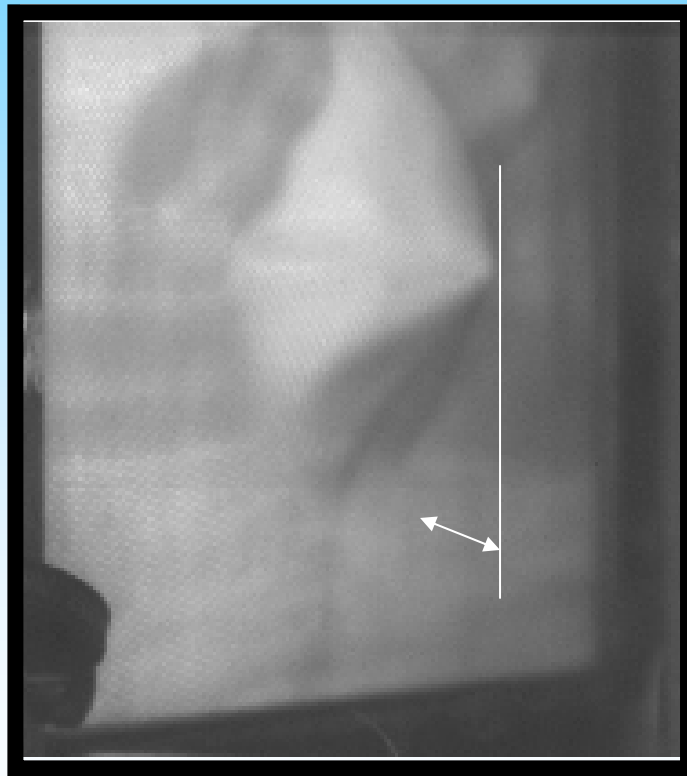
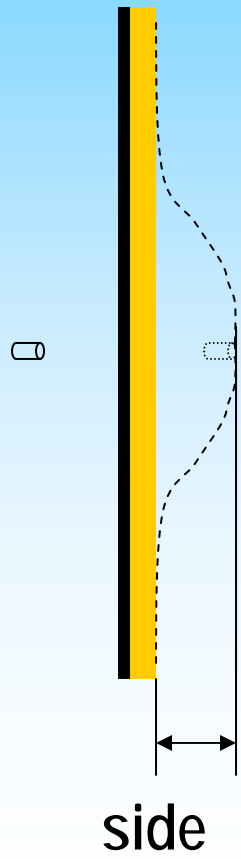


Stage II Post front layer rupture



DYNAMIC DEFLECTION DURING A BALLISTIC EVENT

Projectile must be arrested before major impact force transmitted to skull

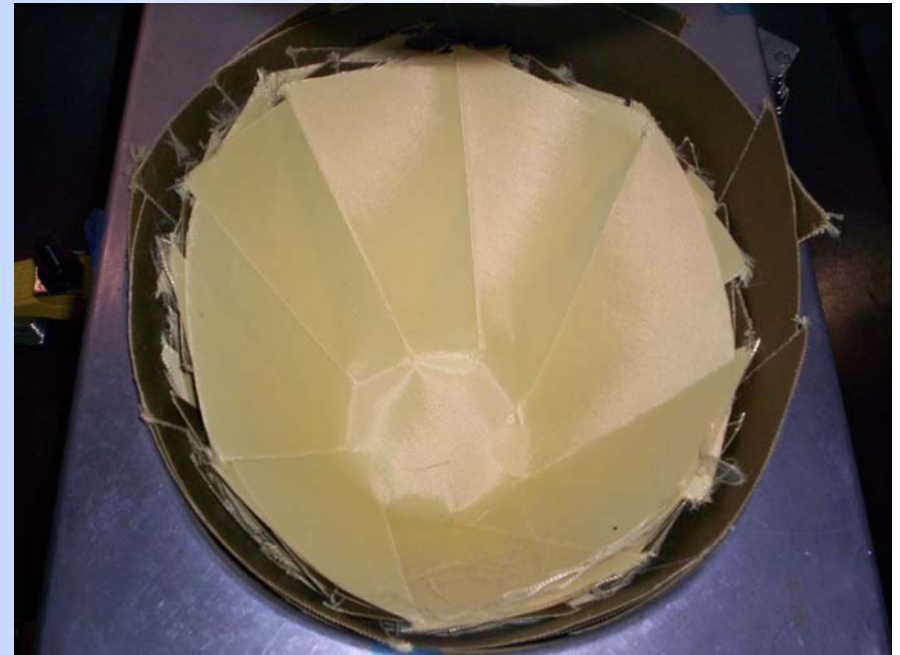


potential for skull fracture

PREFORM PREPARATION AND INSTALLATION IN TOOL



**HYBRIDIZED MATERIALS
(KEVLAR, GRAPHITE FIBER)**

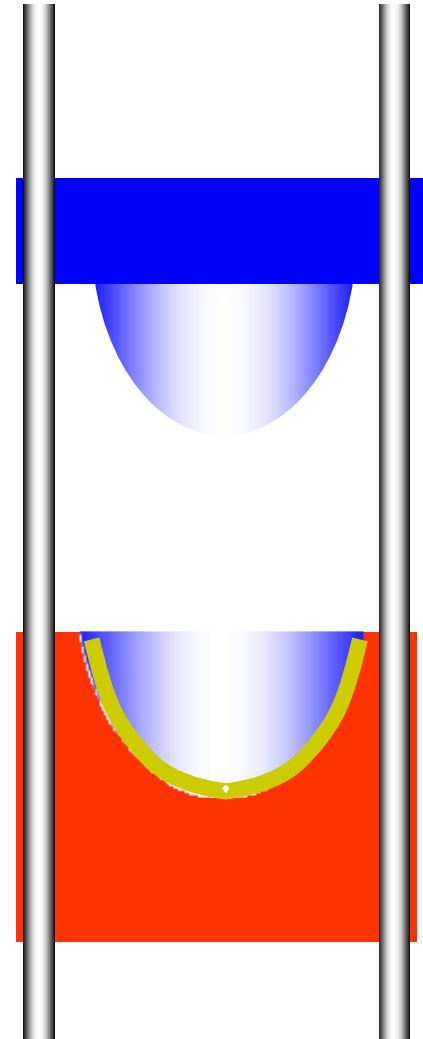


**“FLOWER POTTING” –
INSTALLATION OF
PREFORM IN TOOL**

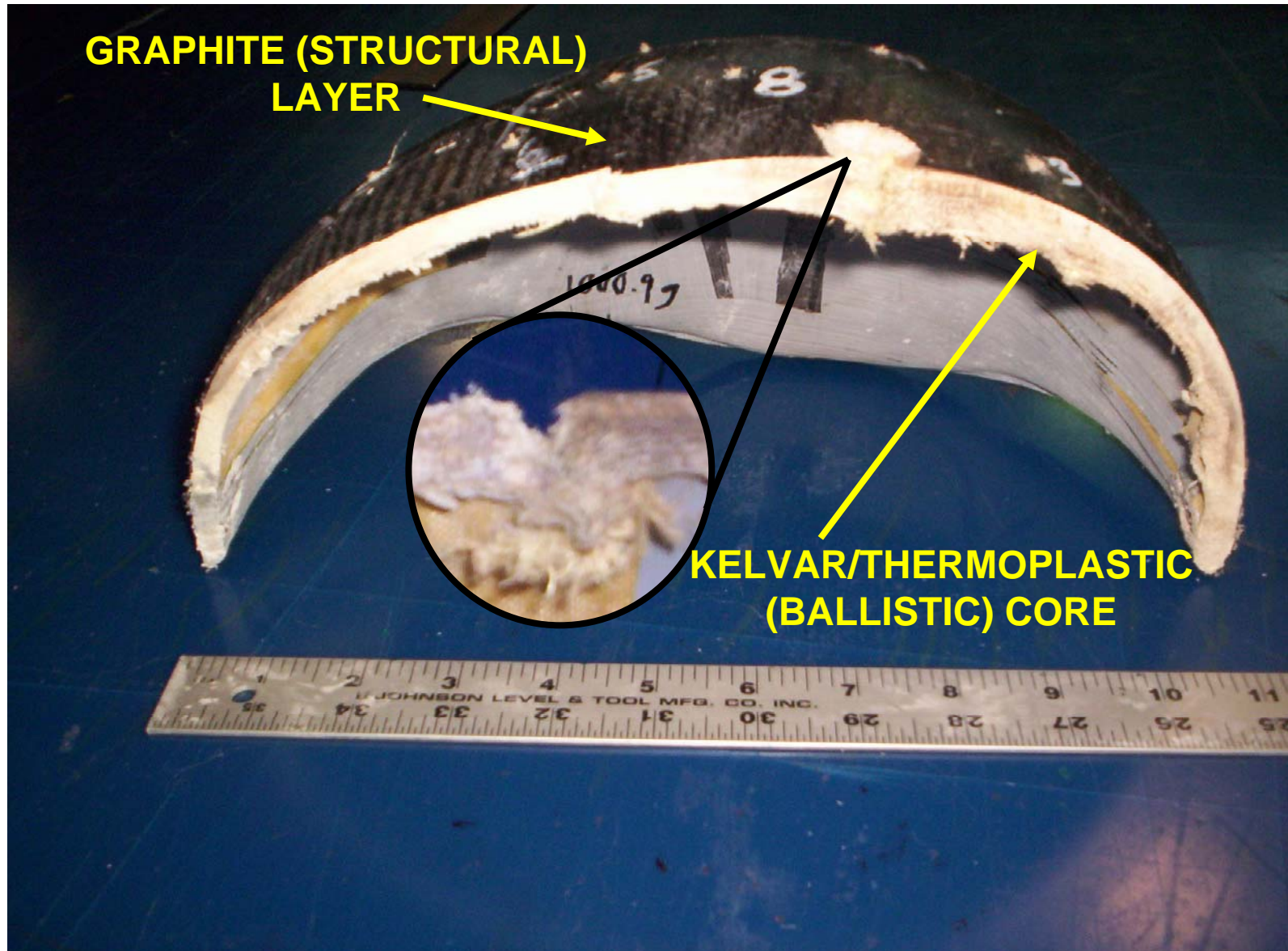
FABRICATION OF HELMET SHELL



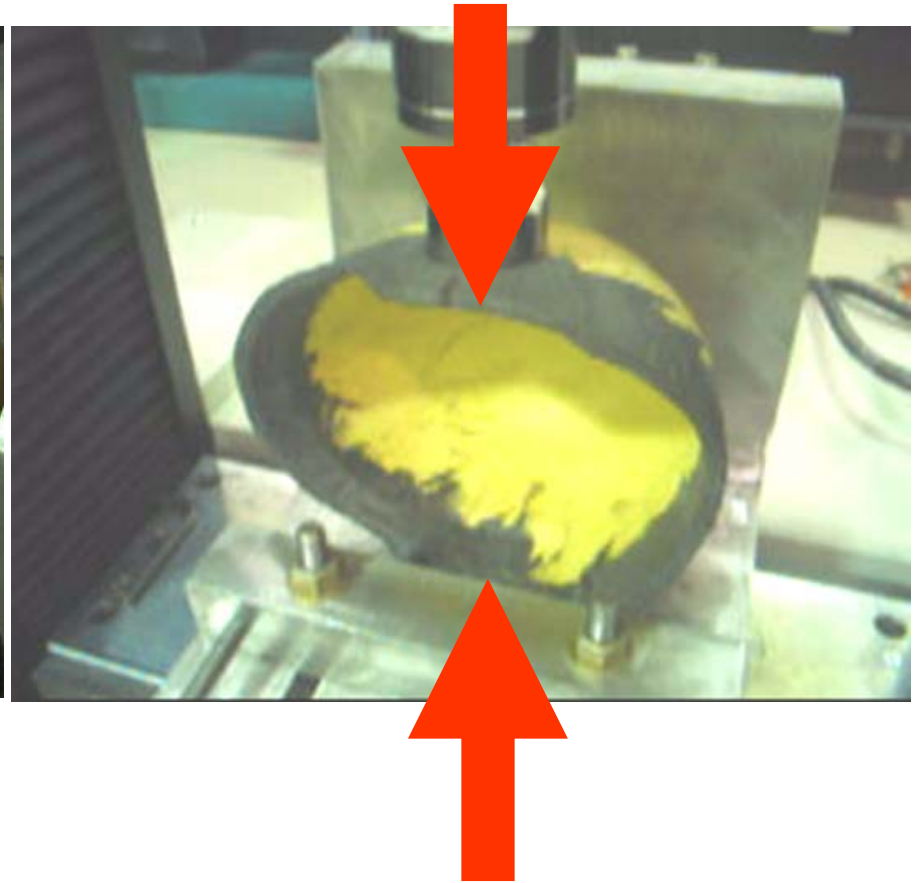
**INSTALLATION OF TOOL &
MATERIAL IN HYDRAULIC
PRESS**



CUT-AWAY OF ACTUAL HYBRIDIZED HELMET

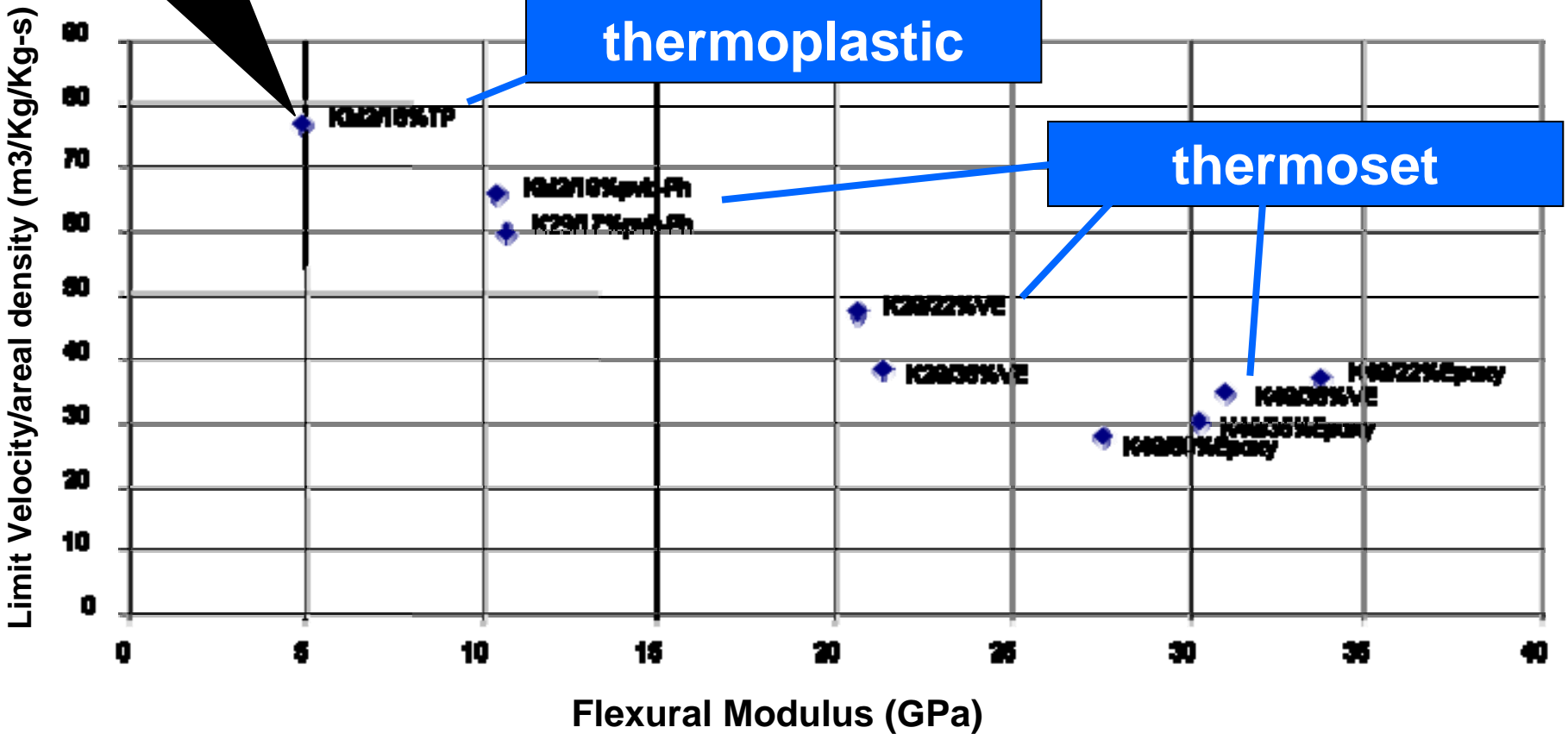


“CRUSH” TESTING OF HELMET VARIANTS

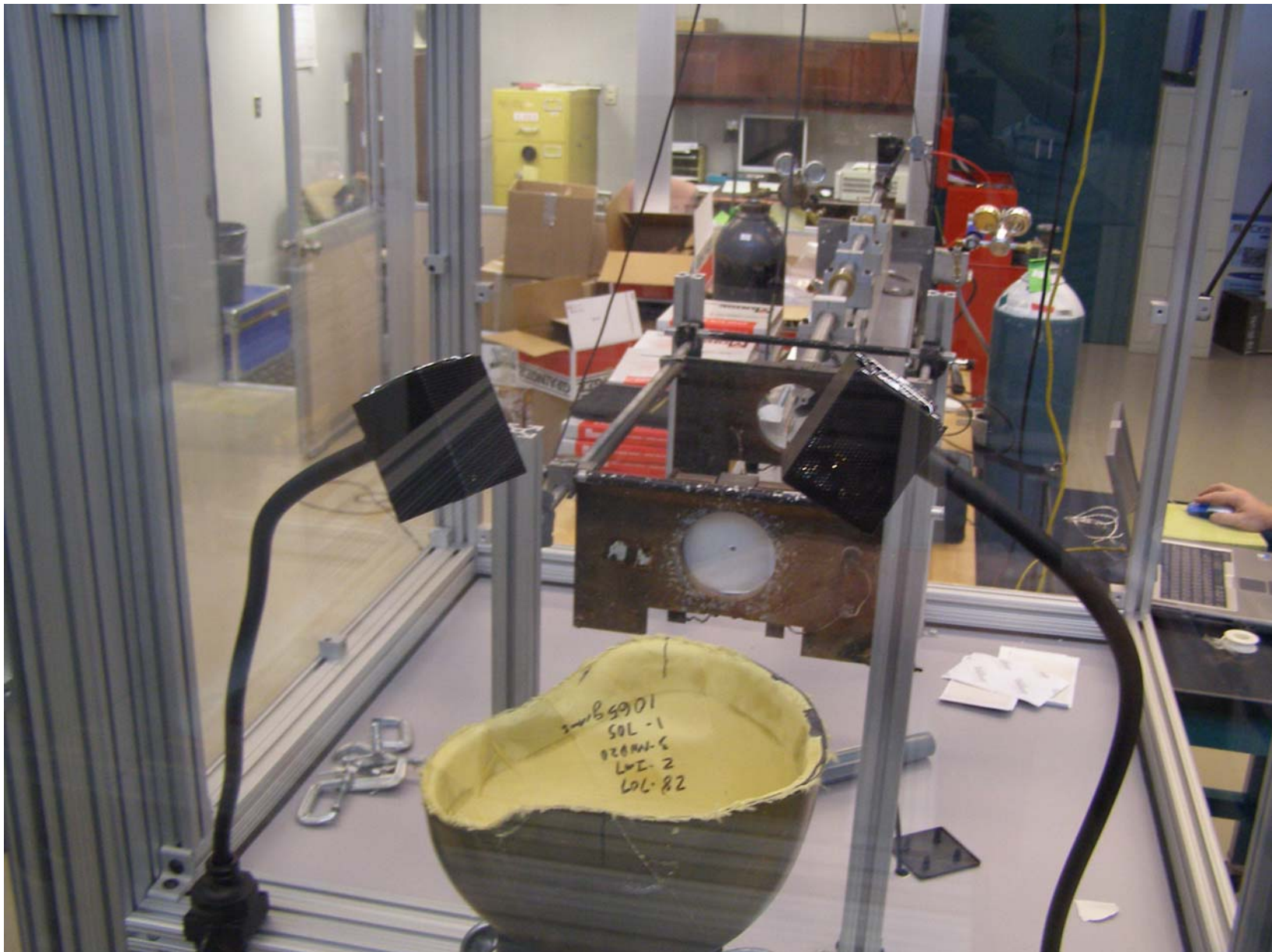


300 pound load applied for 25 cycles

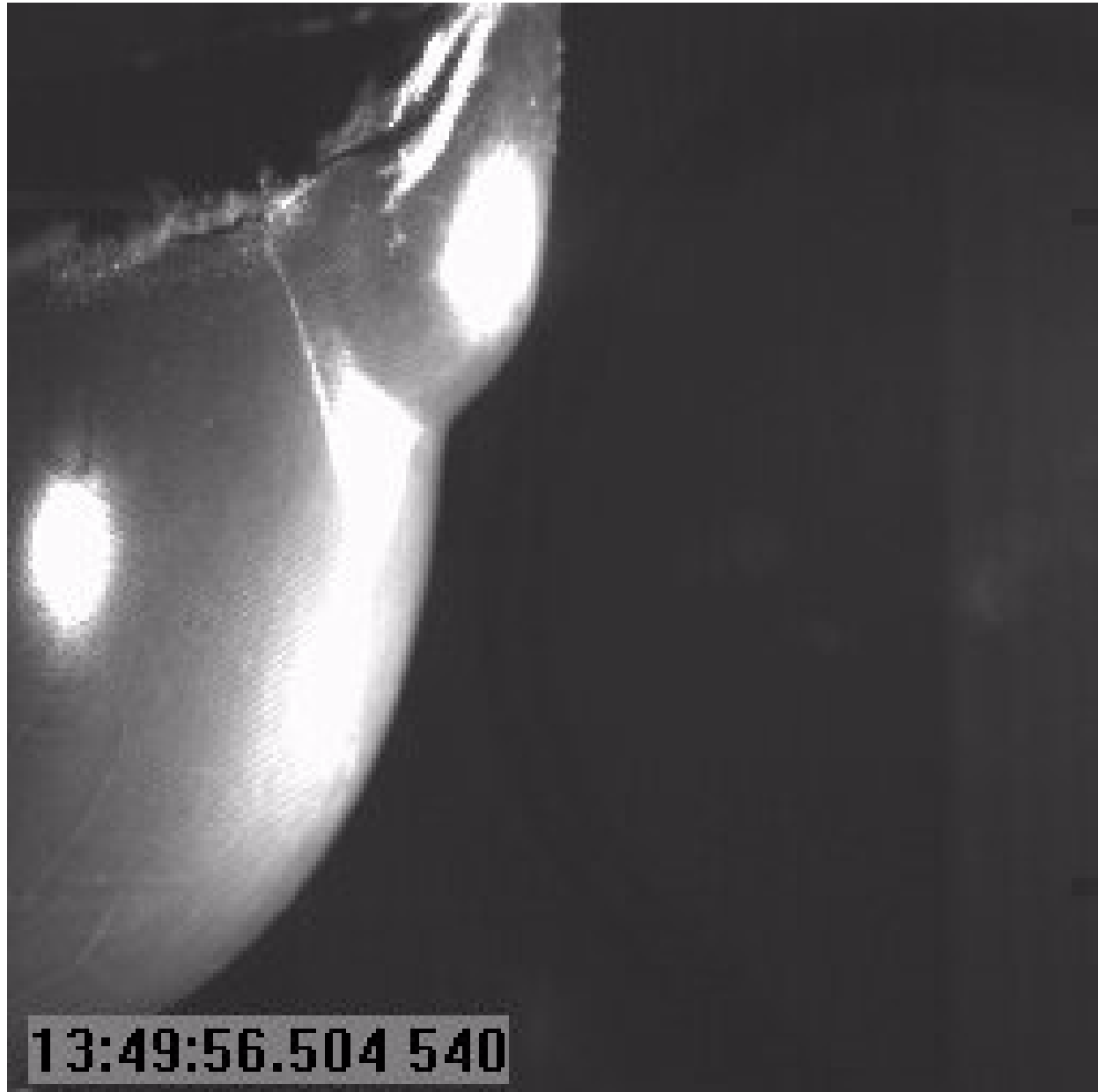
BALLISTIC DATA



BALLISTIC TESTING AND VISUALIZATION APPARATUS



Outside Helmet – Ballistic Impact



Inside Helmet – Dynamic Deflection



RESULTS

PASGT: 19 Ply S735 Kevlar with PVB Phenolic Matrix

Areal Density = 2.3 psf, 17 grain V50 = ~2100 fps

FFW Candidate Recipe: 600 Denier Kevlar KM2 with polyolefin matrix and graphite skin overwrap

Areal Density = 1.75 psf, 17 grain V50 = ~2261 fps

**Improved Fiber, Fiber Architecture, and Matrix
Materials Enable Performance Enhancement**

NOVEL HELMET STIFFENING SYSTEM



- Provides selective stiffening to minimize parasitic weight
- Eliminates need to drill holes into helmet to mount suspension and liner
- Minimizes part count and enables cost effective manufacturing & assembly

Conclusions

- **Current and future headgear systems demand improved ballistic mass efficiency**
- **Candidate thermoplastic-based aramids characterized**
 - *Passed crush test*
 - *Passed preliminary ballistic test/screening*
 - *Identified novel material and design approaches to obtain both ballistic and structural performance at lighter weight*
- **Thermoplastic-based aramids enable:**
 - *Improved ballistic mass efficiency*
 - *Rapid and cost-effective processing methods*
 - *Environmentally friendly/compliant materials & processes*

**Impact on Warfighter: More
Efficient Ballistic Protection**

Acknowledgements



Natick Soldier Center
PEO Soldier
Mentis Science Inc.
Diaphorm LLC
DuPont Company
Intermaterials LLC
Matthew Motoyka (ARL)
Ryan McCuiston (ARL)
Pete Dehmer (ARL)
Scott Grendahl (ARL)